DIGITAL SIGNAL PROCESSING THE TEVATRON BPM SIGNALS

G. Cancelo, E. James, S. Wolbers, Fermilab, Batavia, IL, U.S.A

Abstract

The Beam Position Monitor (TeV BPM) readout system at Fermilab's Tevatron has been updated and is currently being commissioned. The new BPMs use new analog and digital hardware to achieve better beam position measurement resolution. The new system reads signals from both ends of the existing directional stripline pickups to provide simultaneous proton and antiproton measurements. The signals provided by the two ends of the BPM pickups are processed by analog band-pass filters and sampled by 14-bit ADCs at 74.3MHz. A crucial part of this work has been the design of digital filters that process the signal. This paper describes the digital processing and estimation techniques used to optimize the beam position measurement. The BPM electronics must operate in narrow-band and wide-band modes to enable measurements of closed-orbit and turn-by-turn positions. The filtering and timing conditions of the signals are tuned accordingly for the operational modes. The analysis and the optimized result for each mode are presented.

INTRODUCTION

As part of the continuing effort to improve Collider Run 2 performance, the TeV BPM system is being upgraded. A primary motivation for a new system is increased resolution of the position measurement to improve the lattice measurements. Compared to the old BPM system the upgrade increases the 3σ resolution from 150 μm to 20 μm. Replacement of the old system is also motivated by the need for improved reliability. The new BPM system is able to measure the positions of protons in the presence of the antiprotons and the position of the antiprotons in the presence of protons. The main two modes for BPM operation are Closed-Orbit and Turn-by-turn (TBT). The closed orbit measurement determines the average beam position at each BPM location while beam is circulating in the Tevatron. A TBT measurement is used to collect the orbit position of the beam at each BPM location once every revolution for at least 8192 consecutive revolutions [1]. Position measurement is calculated by:

$$p = k.\frac{|A|-|B|}{|A|+|B|} + Offset$$

, where A and B are the signals from the BPM pickups corrected for the imperfect directionality of the pickups. *Offset* corrects for electrical offsets as well as quadrupole magnet center offsets [2].

Figure 1 shows the BPM system block diagram. The Tevatron BPM sensors are two opposing curved stripline plates approximately 18 cm long along the beam. Each plate subtends approximately 110 degrees of the full

circle. The circular aperture of the pair is 6.6 cm. The BPM signals pass through the Tevatron Filter board for amplitude conditioning and band pass filtering. The filter is centered at the 53.104 MHz accelerator RF frequency with a bandwidth of approximately 10 MHZ. The signals are sampled, down converted and digitally filtered by a commercially available Echotek board [3]. The VME sub rack controller is a Motorola MVME2400 type processor that controls the data acquisition process. The system timing is controlled by the VME BPM Timing Generator Fanout module. The TGF timing is based on three Tevatron timing signals: the Tevatron RF Clock (RFClk), the Tevatron Beam Sync (TVBS), containing some Tevatron commands and the encoded turn marker, and the Tevatron Clock (TClk) containing accelerator-complex-wide commands.
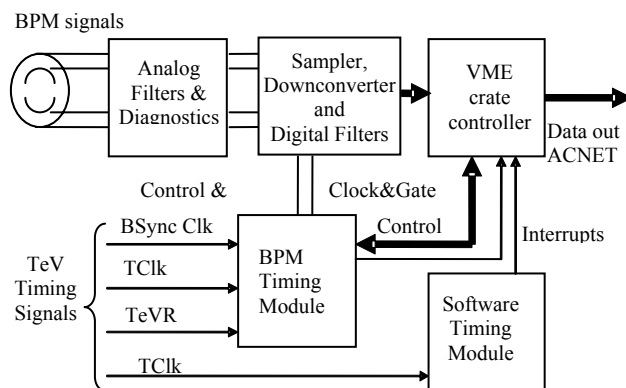

Figure 1: TeV BPM system block diagram.

This paper reports on the design and performance of the digital filters that process the down converted signals. The rest of the Tevatron BPM system is reported somewhere else [8].

THE TEVATRON BPM SIGNALS

The BPM pickup signal is a "doublet" as shown in Figure 2. For analytical purpose the doublet can be modeled by the sum of 2 Gaussians displaced in time:

$$s(t) = A.\left[e^{-(t/\sigma_s)^2} - e^{-(t-t_s)^2/\sigma_s^2}\right] \quad (1)$$

The value of σ_s 3 ns at 150 GeV and 1.6-2.5 ns at 980 GeV for coalecsed bunches. t_s is about 3.3 ns The first filtering stage of the Tevatron BPM system is a pass-band ringing filter centered at 53.104MHz. Since the doublet's width is only a few ns, the purpose of the ringing filter is to generate a signal long enough to be used for beam position measurement with low error (Figure 3). The filters transfer function is

$$h(t) = h_0 e^{-(t-t_0)^2/\sigma^2}.\cos(\omega_c t + \phi) \quad (2), \text{ where}$$

ω_c=53.1MHz, σ=33ns and t_0=120ns. Some constants

have been determined experimentally [5]. The output of the ringing filter is the convolution of (1) and (2):

$$H(\omega) = \frac{h_0}{2}\sqrt{\pi}\sigma \left[e^{-j[t_0(\omega-\omega_c)-\phi]} e^{-\frac{\sigma^2}{4}(\omega-\omega_c)^2} + e^{-j[t_0(\omega+\omega_c)+\phi]} e^{-\frac{\sigma^2}{4}(\omega+\omega_c)^2} \right]$$
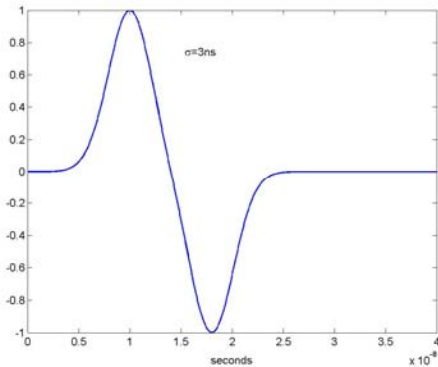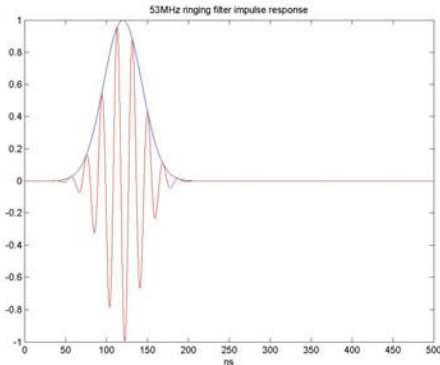

Figure 2: Doublet signal from pickup.

Figure 3: 53MHz analog filter output.

A typical Tevatron beam load has 3 trains of 12 bunches separated by abort gaps as shown in Figure 4. That beam structure is periodic with T~6.986μs. So, its spectrum has lines at 1/T~144KHz, the frequency at which the train of bunches repeat. The BPM system must be able to work with other beam load configurations with fewer bunches.
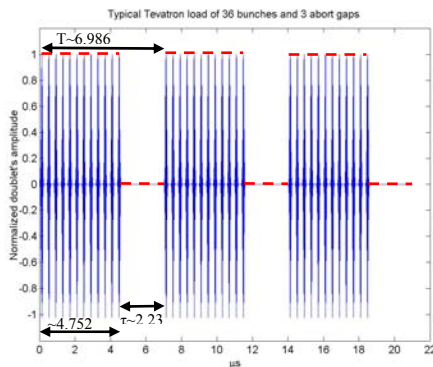

Figure 4: 36 bunch TeV Beam load.

THE ENVELOPE FILTER

The on-line filtering of the A and B signals for beam position measurement is a combination of digital filtering and data processing on firmware. Since beam position variations are "slow" with respect to the signal spectrum fastest components, the envelope of the batch of bunches is enough to estimate position (1st harmonic is at ~150KHz). The so called "Envelope Filter" takes advantage of the digital filters provided by the TI down-converter and filter Graychip [4] in the Echotek boards. The digital filters work on the I (in-phase) and Q (in-quadrature) outputs of the down-converter sections. Each Graychip has four individual channels that can be combined to form wider band filters. Each Graychip channel is a cascade of three filters, a 5-stage Cascade Integrator Comb (CIC) filter and two Finite-Impulse-Response (FIR) filters called CFIR and PFIR. The CIC's transfer function is[6][7]:

$$H(z) = H_I^N(z) H_C^N(z) = \frac{\left(1-z^{-D}\right)^N}{\left(1-z^{-1}\right)^N} = \left[\sum_{k=0}^{D-1} z^{-k} \right]^N, \text{ where } H_I$$

and H_C are transfer functions of the integrator and comb stages respectively. The only design parameter available for the CIC filter is the decimation rate, which can be used to control the filter's cutoff frequency. The CFIR filter is a short FIR filter mainly used to compensate for the large drooping in the amplitude transfer of the CIC filter. The PFIR, instead, has a fast transition band response. The cutoff frequency of the filter has been chosen equal to 300KHz. Figure 5 shows the filter's frequency responses.
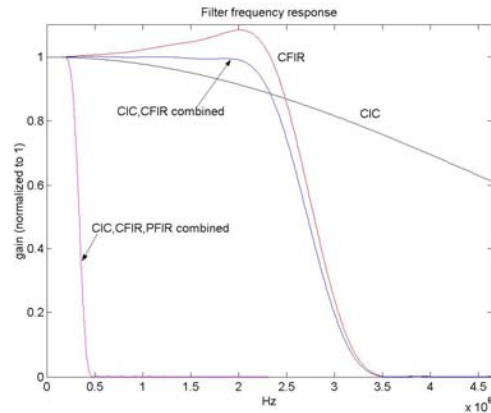

Figure 5: Envelope Filter frequency response.

Figure 6 shows signals |A| and |B| obtained computing the filtered I and Q. The figure also displays beam intensity |A|+|B| and estimated position |A|-|B|/|A|+|B|. There are about 32 samples per batch. The second part of the Envelope Filter implements a non-linear filter which picks only the I and Q samples whose intensity (|A|+|B|) is over a threshold α. This filtering method was chosen over the optimal linear matched-filter because the number of samples is large enough to be able to keep those with good S/N ratio. Since the intensity function is smooth, the threshold α can be easily calculated. The Envelope Filter

performance is better than the Cramer-Rao lower bound. The Envelope Filter also averages Is and Qs to reduce the number of samples that are readout from the Echotek's memory. The number of samples averaged in the FPGA is defined by the desired digital bandwidth at the output of the Echotek.
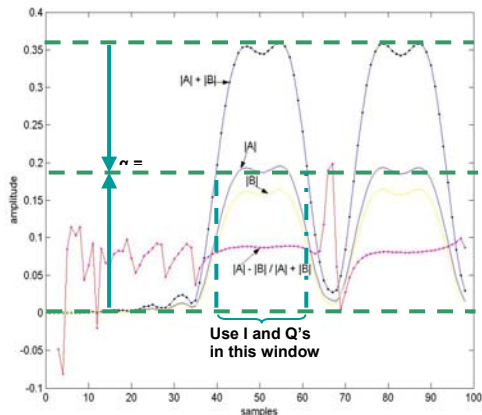

Figure 6: Filtered A, B, intensity & position waves.

ENVELOPE FILTER PERFORMANCE

Figures 7, and 8 show the performance of the Envelope Filter for bunch loads from 1 to 36. In order to generate enough statistics each bunch load test represents a run of more than 10,000 input samples. B signal is smaller than A by about 84μm. It is expected that the Envelope Filter performs better for bunch loads with more bunches because the digital filter's bandwidth is only 300KHz. However, it can be appreciated in Figure 7. that the Envelope Filter responds very well to bunch loads with a small number of bunches. The major effect in the filter's performance is an increase in the sigma of the error distribution of position measurement. The larger error in the position measurement for loads with fewer bunches can be compensated by a larger average in the FPGA or in the offline processing, or increasing the Envelope Filter's bandwidth.
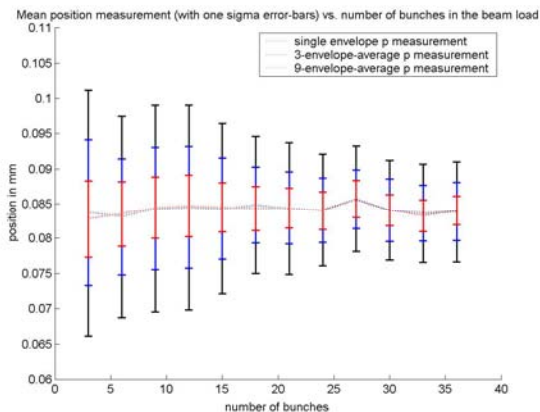

Figure 7: Position error distribution measurements.

Figure 7 shows μ and σ of the position error distribution for three different FPGA implementations of the

Envelope Filter that combines a different number of I-Q pairs as follow:

- Single envelope p measurements = one I-Q pair ~ every 7usec (~142KHz)
- 3-envelope avrg. P measurements = one I-Q pair per lap, ~21usec (~45KHz)
- 9-envelope avrg. P measurements = one I-Q pair every 3 laps, ~63usec (~18KHz)

Figure 8 shows the sigma of the error distribution in the position measurement. All 3 sigma trends should be monotonic. The few points that fail to achieve that are probably due to the some non-Gaussian noise in the test-stand.
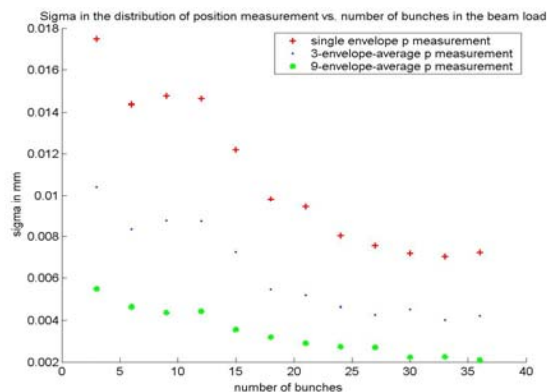

Figure 8: σ error in Position distribution measurements.

In every case the performance of the Envelope Filter is excellent. Figure 8 shows the Envelope Filter can run at 18 KHz (i.e. averaging I-Q pairs for 3 accelerator laps) providing a position measurement with an error less than 2μm for full beam load and better than 6μm for any load.

REFERENCES

[1] Martens M. et al., "Tevatron Beam Position Monitor Upgrade Requirements", Fermilab Beams Doc. #554, Oct. 2003.
[2] Kutschke, R. "Tevatron BPM Upgrade Calibration Specifications: Part II", Fermilab Beams Doc. #1205, Ago. 2004.
[3] Echotek, "ECDR-GC814-FV2 User Manual", Echotek Corporation, March 2003.
[4] Texas Instrument, "Graychip 4016 Data Sheet rev1.0", Aug. 2001.
[5] G. Cancelo, "Some models of the BPM signal", Fermilab Beams-doc-1590, Feb 25, 2005.
[6] E. Hogenauer, "An economical class of digital filters for decimation and interpolation", IEEE Transactions on ASSP, vol ASSP-29, No 2, April 1981.
[7] G. Cancelo, "The CIC filter", Fermilab Beams-doc-1591, Feb 25, 2005
[8] Wolbers S. et al., "Tevatron Beam Position Monitor Upgrade, submitted to IEEE-PAC 2005, TOPC004, May 16-20 2005.